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Key Points:
- Unified methodology for metastatistical extreme value analysis of subdaily precipitation across durations is presented
- The simplified formulation of the method permits to analyze extremes emerging from tail of ordinary events rather than entire distribution
- Consistent definition across durations yields ordinary events which scale with the same scaling exponent of annual maxima

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A Unified Framework for Extreme Subdaily Precipitation Frequency Analyses Based on Ordinary Events

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Abstract The metastatistical extreme value approach proved promising in the frequency analysis of daily precipitation from ordinary events, outperforming traditional methods based on sampled extremes. However, subdaily applications are currently restrained by two knowledge gaps: It is not known if ordinary events can be consistently examined over durations, and it is not clear to what extent their entire distributions represent extremes. We propose here a unified definition of ordinary events across durations and suggest the simplified metastatistical extreme value formulation for dealing with extremes emerging from the tail, rather than the entire distributions, of ordinary events. This unified framework provides robust estimates of extreme quantiles (<10% error on the 100 yr from a 26 yr long record) and allows representations in which ordinary and extreme events share the scaling exponent. Future applications could improve our knowledge of subdaily extreme precipitation and help investigate the impact of local factors and climatic forcing on their frequency.

Plain Language Summary We propose here a unified methodology to quantify the intensity of extreme rainfall of short duration, such as events expected to occur on average once every 100 yr. As opposed to alternative methods in literature, we rely on the simultaneous analysis of all everyday rainfall events, which, being much larger in number than extremes, were shown to provide improved estimates for daily rainfall. We show that, under our approach, the hypothesis of everyday and extreme events being similar enough holds also for short-duration rainfall. Application of our method to 26 yr of data from an individual station reproduces analyses based on more than 150 yr of observations from multiple nearby stations, with less than 10% error on the estimation of rain intensities expected to occur on average once every 100 yr, which are not directly quantifiable from the 26 yr of observations. The proposed methodology could help improve our knowledge of short-duration rainfall extremes, with implications for water resources and risk management, and could help investigate the impact of climate change on extreme rainfall events.

1. Introduction

The metastatistical extreme value (MEV) framework was recently proposed for the frequency analyses of extremes under pre-asymptotic conditions. The method relies on the concept of ordinary events, which are defined as all the independent realization of the process of interest, and showed promising results for modeling extreme daily precipitation. However, its application to subdaily durations is currently restrained by two knowledge gaps: It is not known if and how ordinary events can be consistently examined over multiple durations, and it is not clear to what extent the entire distributions of ordinary events can be extended to extremes. We propose a unified framework for using ordinary events across durations and suggest a viable methodology for dealing with extremes emerging from the tail, rather than the entire distributions, of ordinary events.

MEV relies on the hypothesis that the extremes of the variable of interest emerge from the yearly distributions of underlying ordinary events, which are sampled a finite number of times every year (Marani & Ignaccolo, 2015). Once the cumulative distributions of the ordinary events $F(x, \theta_j)$, where θ_j are the distribution parameters, are known for every year $j = 1...M$, the extreme values cumulative distribution can be written as: $\zeta(x) = \frac{1}{M}\sum_{j=1}^{M} F\left(x, \theta_j\right)^{n_j}$, where n_j is the number of ordinary events observed in the jth year (Zorzetto et al., 2016). The framework can include any class of distributions for F and allows to consider multiple types of ordinary events, for example, nontropical and tropical cyclones, to derive compound extreme value distributions (Marra et al., 2019; Miniussi et al., 2020). Making use of the full available data record, MEV also largely decreases the parameter estimation uncertainty and the stochastic uncertainty related to the sampling of extremes.

It can be shown that when the interannual variability of the ordinary events can be neglected (i.e., $\theta_j \approx \theta_k, \forall\, j,k$) and the focus is on extreme quantiles (i.e., $F \to 1$), the interannual variability of the number of yearly events also becomes negligible. In these conditions, a simplified MEV formulation (SMEV), closely resembling ordinary statistics, can be written: $\zeta(x) \approx F(x, \theta)^n$, where n is here the average number of ordinary events per year (Marra et al., 2019). SMEV was originally proposed as an instantaneous limit ($M \to 0$) of MEV for the analysis of nonstationary processes. However, when tested for extreme value analyses on observational records, SMEV was found to perform similarly, even if less accurately than MEV, and to be preferable when the small number of ordinary events per year prevents accurate estimation of parameters for individual years ($n \lesssim 20$) (Miniussi & Marani, 2020; Schellander et al., 2019). Owing to the largely increased data sample used to estimate the distribution parameters (all years are used together), SMEV permits to focus on the tail of the ordinary events distribution by left-censoring the data (Marra et al., 2019). It should be noted that this is not equivalent to threshold exceedance methods: SMEV describes tails which include large portions of the data and whose definition accounts for the number of ordinary events in the data sample, while threshold exceedance methods require thresholds which asymptotically tend to the upper limit of the distribution support and discard all the information below threshold (Davison & Smith, 1990). It was recently shown that MEV and SMEV can be related to more general distributions of serially correlated order statistics (Serinaldi et al., 2020).

So far, MEV methods have been mostly used for the analysis of extreme daily precipitation relying on Weibull distributions to describe the ordinary events (e.g., Marani & Ignaccolo, 2015; Miniussi & Marani, 2020; Zorzetto et al., 2016). Results showed a number of advantages over traditional methods based on the sampled extremes: (i) rare quantiles, corresponding to return periods longer than the available data record, are estimated with significantly reduced errors; (ii) short records are sufficient to obtain robust estimates; (iii) the method is less sensitive to measurement errors typically affecting extremes (Marra et al., 2018; Miniussi & Marani, 2020; Schellander et al., 2019; Zorzetto et al., 2016; Zorzetto & Marani, 2020). However, two knowledge gaps currently restrain the application of MEV to subdaily durations. First, the only method so far proposed to define subdaily ordinary events is based on the temporal autocorrelation of the individual time series and does not permit to consider multiple durations together (Marra et al., 2018). Second, the results reported above only pertain to extremes emerging from the entire yearly distributions of ordinary events. This assumption is in contrast with results showing that subdaily precipitation is better described by more general distributions, whose tails only can be approximated by stretched-exponential, for example, Weibull, or power-type distributions (e.g., Papalexiou, 2018; Papalexiou et al., 2018). Extending the applicability of MEV to subdaily durations by means of a unified methodology that allows to examine ordinary events across durations could pose the bases for more general frameworks relying on the scaling properties of ordinary events. This could improve our understanding of extreme precipitation at the global scale and provide more accurate information for hydraulic infrastructure design and risk management.

Here, we address the current knowledge gaps restraining the use of MEV methods on subdaily durations by (a) proposing a consistent definition of ordinary events which allows scaling representations across durations, and (b) suggesting SMEV as a viable option for dealing with extremes emerging from the tail of the ordinary events distribution, as opposed to their entire distributions. We evaluate the robustness of the proposed MEV and SMEV approaches on a study case in the southeastern Mediterranean coast for which 26 yr of 10 min data are available. We rely on regional estimates of rare quantiles from nine stations as a reference.

2. Methods

We propose to define ordinary events based on *storms*, that is, consecutive wet time intervals separated by dry hiatuses whose length is to be determined based on the climatology of the region. Once storms are defined, ordinary events are computed as the maximum intensities observed within each storm using moving windows of the duration of interest. In this way, a storm will correspond to an individual ordinary event for each of the examined durations. Such a definition has two main advantages: First, the number of

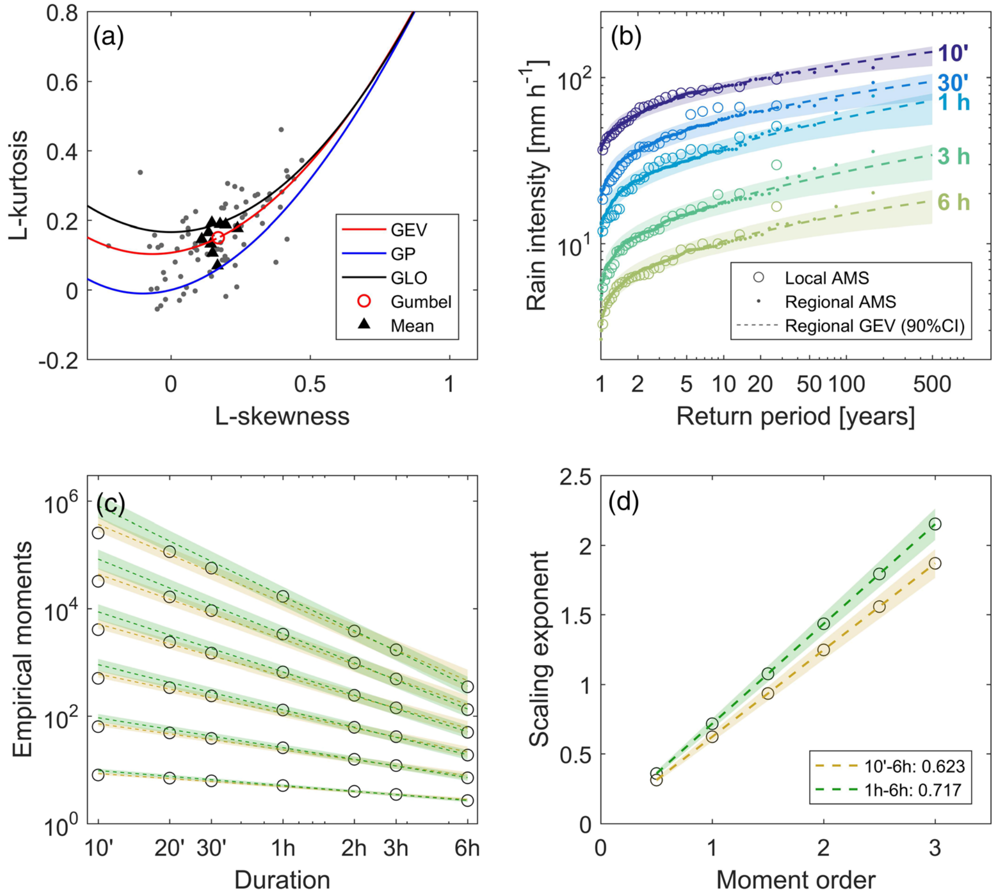

Figure 1. Regional analysis and scaling properties of the annual maxima. (a) L-moments ratio diagram for all the stations and durations; the theoretical moments for generalized extreme value (GEV), generalized Pareto (GP), and generalized logistic (GLO) distributions are shown; the mean L-moment ratios for each duration are shown as black triangles. (b) Regional GEV distributions (dashed lines) estimated using the regional L moments framework by Hosking and Wallis (1997); shaded areas show the 90% confidence interval obtained via bootstrap with replacement among the regional annual maxima (AMS); circles show the AMS observed at Zykhron Yaaqov station (frequency is estimated using the Weibull plotting positions), while dots show the AMS from all the nine stations rescaled to the Zykhron Yaaqov mean. (c) Raw moments of the AMS for the examined durations and for moment orders 0.5, 1, 1.5, 2, 2.5, and 3. Colored lines show the regressions obtained using the full temporal domain (10 min to 6 hr; orange, shaded area represent the 90% confidence interval from 10^3 bootstrap samples with replacement among the years) and the 1–6 hr interval (green); (d) scaling exponent of the AMS obtained using the full temporal domain (10 min to 6 hr; orange) and the 1–6 hr interval (green).

ordinary events remains consistent across durations, thus permitting to examine the properties of the ordinary events and of their distributions across durations; second, ordinary events can be directly related to meteorological features, thus providing the potential for consistently using them over a region and for examining their characteristics at multiple scales.

Series of 10 min precipitation data are collected for nine quality-checked automatic stations in the southeastern Mediterranean coast, with 164 yr of record in total. Distance between the stations ranges between 1.5 and 70 km (27 ± 16 km), and individual records span 10 to 26 yr (18.2 ± 6.1 yr). Homogeneity of the region was ensured using the method based on the coefficient of L variation recommended by Hosking and Wallis (1997) ($H < 0.25$ for all durations), so that the stations could be collectively used in a regional framework to estimate extremely low yearly exceedance probabilities. Reference quantiles are computed from the nine stations using the regional L moments method by Hosking and Wallis (1997) and the generalized extreme value (GEV) distribution by normalizing the annual maxima over their mean values (Figure 1).

Following previous studies in similar climates, we require at least six dry-hour hiatuses to separate storms (Restrepo-Posada & Eagleson, 1982; Tarolli et al., 2012), but general applications should use a definition based on the local climatology. Dry hiatuses are here defined as consecutive time intervals lower than the minimum rain amount reported in the data, 0.1 mm. Storms lasting less than 30 min are removed to avoid individual tips of the rain gauge to be considered as a storm. We focus on durations between 10 min and 6 hr, a choice driven by the temporal resolution of the data and the dry hiatus used to separate storms.

MEV and SMEV are here applied *at site* focusing on the longest recording station (Zikhron Yaaqov, 26 yr). Complying with previous MEV applications, ordinary events are described using Weibull distributions in the form $F(x;\lambda,\kappa) = 1 - e^{-\left(\frac{x}{\lambda}\right)^{\kappa}}$, where λ and κ are the scale and shape parameters, respectively (Zorzetto et al., 2016). Such a model was shown as appropriate for the here-examined region (Marra et al., 2019). Three MEV parameters are obtained for every year: λ_j and κ_j are estimated from all the yearly ordinary events by using the method of the L moments (Hosking, 1990), and n_j as the number of ordinary events in the *j*th year. Extreme quantiles are then computed by numerically inverting the MEV cumulative distribution function (Marra et al., 2018; Zorzetto et al., 2016).

Since it neglects interannual variability in the parameters, SMEV only requires three parameters: λ and κ are estimated left-censoring the low portion of the ordinary events, that is, ignoring their intensities while retaining their weight in probability and using a least squares regression in Weibull-transformed coordinates on the remaining data points (Marani & Ignaccolo, 2015), while n is the mean number of ordinary events per year ($n = \frac{\sum n_j}{M}$). It is worth noting that, when based on Weibull, the SMEV distribution becomes an exponentiated Weibull distribution (Nadarajah et al., 2013). In order to focus on the ordinary events tail, a definition of the portion of data representing the tail is required. The definition is case dependent and should be selected using sensitivity analyses as described in Marra et al. (2019): The portion of data constituting the tail should be large enough to avoid the stochastic sampling uncertainties characterizing the largest events and small enough to only include identically distributed, in our case Weibull-distributed, data. Marra et al. (2019), presenting the SMEV idea, showed that a definition of the tail as the largest 45–20% of the ordinary events is appropriate for the study region, providing virtually indistinguishable results. Following this study, the ordinary events tail is here defined as the largest 25% of the ordinary events (Marra et al., 2019). Extreme quantiles are computed inverting the SMEV cumulative distribution function. In addition, in order to better evaluate the robustness of SMEV to represent the distribution of out-of-sample extremes, a second set of parameters and quantiles is derived by also censoring all the annual maxima. As in the case of the left-censoring, this is done by ignoring the annual maxima intensities while retaining their weight in probability. The obtained results are thus quantitatively independent from the observed annual maxima. For all methods, confidence intervals in parameters and quantiles are computed via bootstrap with replacement (10^3 repetitions) among the years in the record (Overeem et al., 2008).

3. Results and Discussion

Application of MEV and SMEV to the here defined subdaily ordinary events provides robust estimates of extreme quantiles (Figure 2), with the estimated MEV (blue solid line and 90% confidence interval) and SMEV (red) distributions being generally consistent with the regional reference and only MEV slightly underestimating quantiles for 1 and 3 hr durations, as the reference lies outside of the 90% confidence interval. Thanks to the focus on the ordinary events tail, SMEV provides more accurate estimates (<10% error on the 100 yr quantiles for all durations, <12.5% for 500 yr) than MEV (<20%) but, due to the smaller data sample used to estimate the parameters, is characterized by larger uncertainty. Quantiles obtained independently from the observed annual maxima (magenta dashed lines) lie within the confidence interval of SMEV and never exceed 20% error, even for 500 yr return levels. Examining these errors, one should remember that the reference, that is, the regional GEV, is itself an estimate of the true distribution. The observed annual maxima (black dots, plotted using the Weibull plotting positions) lie within the area in which we expect to see 90% of the annual maxima *if* they were actually sampled from SMEV (shaded in gray, obtained from 10^3 random sampling from SMEV). These observations support the robustness of the SMEV approach.

The dependence of MEV and SMEV parameters on duration is presented in Figure 3, noting that blue-shaded area represents the 90% interannual variability of MEV parameters and red and gray areas represent the 90% confidence intervals (bootstrap among the years) of SMEV and nonzero tail parameters, respectively. It is interesting to see a decrease of the shape parameter with increasing duration (Figure 3b). This translates into heavier tails of the distribution of ordinary events at longer durations and, due to the consistent definition of ordinary events, of the resulting extreme value distribution. This

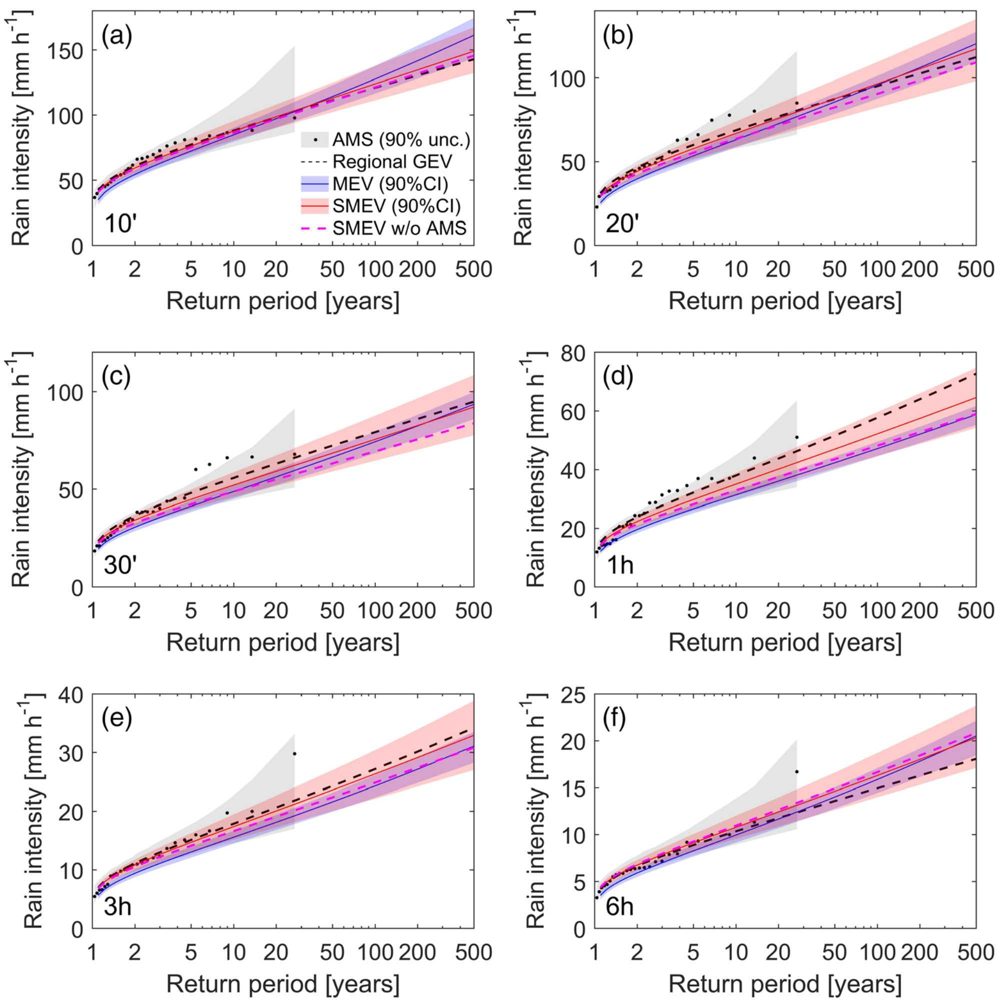

Figure 2. Quantiles estimated using MEV (blue solid line), SMEV (red solid line) for 10 min to 6 hr durations (a–f); blue- and red-shaded areas show the corresponding 90% confidence intervals (10^3 bootstrap samples with replacement among the years). Black dots show the observed annual maxima (AMS), and dashed black line the regional GEV estimate obtained from nine stations in the region (reference). Shaded in gray are the areas in which 90% of the annual maxima are expected to lie *if* they were sampled from SMEV. Magenta dashed lines represent quantiles obtained using SMEV and censoring the annual maxima.

seemingly contradicts previous results in which the tail of nonzero time intervals was examined (e.g., Papalexiou et al., 2018). However, examination of the Weibull parameters describing the largest 10% of all nonzero wet time interval, that is, the tail definition of Papalexiou et al. (2018), shows that this apparent contradiction is explained by the dramatic change in the number of nonzero time intervals per year (Figure 3c). Using a consistent definition of the ordinary events in which their number is the same across durations, MEV and SMEV scale parameters are described by power law functions of duration which share the scaling exponent with annual maxima above 1 hr (Figures 3a and 1). Notably, this is the temporal domain in which the simple scaling, that is, power law, behavior of annual maxima is generally considered more robust (Burlando & Rosso, 1996; Ceresetti et al., 2010). This property suggests that extremes are indeed samples from the tail of the ordinary events and opens MEV methods to applications in which multiple durations are used simultaneously (e.g., Burlando & Rosso, 1996; Emmanouil et al., 2020; Innocenti et al., 2017; Langousis & Veneziano, 2007). Overall, the use of consistent ordinary events across durations permits to examine the scaling behavior in all rain events, including different, if any, behaviors between extreme and ordinary events.

We conclude showing further evidence for the emergence of extreme subdaily precipitation from the tail of ordinary events. Figure 4a presents a Weibull plot, in which Weibull distributions appear as linear, showing the Weibull distributions whose parameters are estimated explicitly censoring the observed annual maxima

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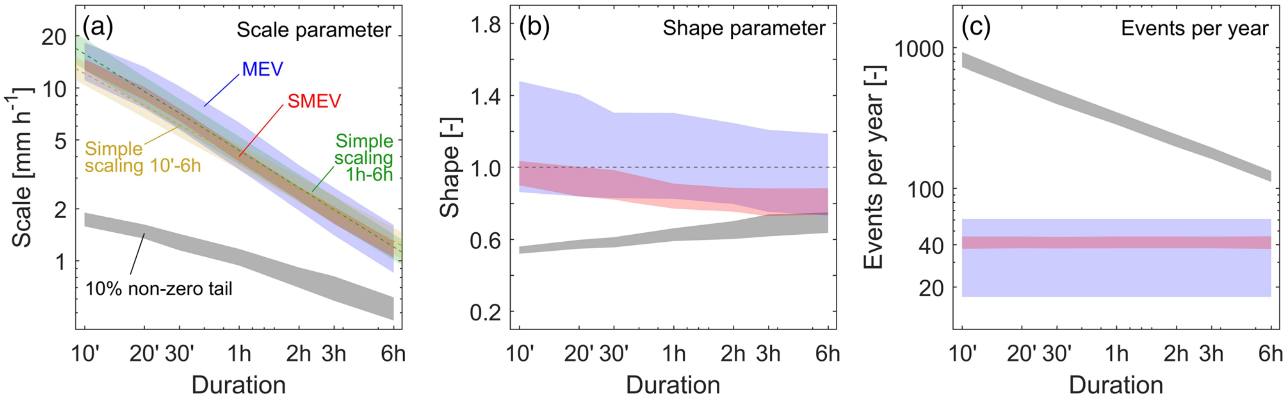

Figure 3. MEV and SMEV parameters as a function of duration; blue-shaded area represents the 90% interannual variability of MEV parameters, and red and gray areas represent the 90% confidence intervals (bootstrap among the years) of SMEV and 10% nonzero tail (as in Papalexiou et al., 2018) parameters, respectively. (a) Scaling of the scale parameters with duration for MEV (blue), SMEV (red), and 10% nonzero tail (gray). Simple scaling relations from annual maxima are superimposed (10 min to 6 hr in orange, 1–6 hr in in green, see Figure 1); within the uncertainties, MEV and SMEV scale parameters share the scaling exponent with annual maxima, especially the 1–6 hr (green); (b) dependence of the shape parameters with duration. The shape parameter of the nonzero tail increases with duration as reported by other studies (e.g., Papalexiou et al., 2018), while an opposite behavior is reported for the MEV and SMEV; for the case of SMEV, the decrease is larger than the parameter estimation uncertainty; (c) dependence of the number of ordinary events per year with duration. The proposed definition makes their number independent on duration (~40 events per year in this case). The marked decrease of the number of nonzero time intervals (gray) explains the different behaviors observed for the shape parameters between nonzero tail and MEV methods.

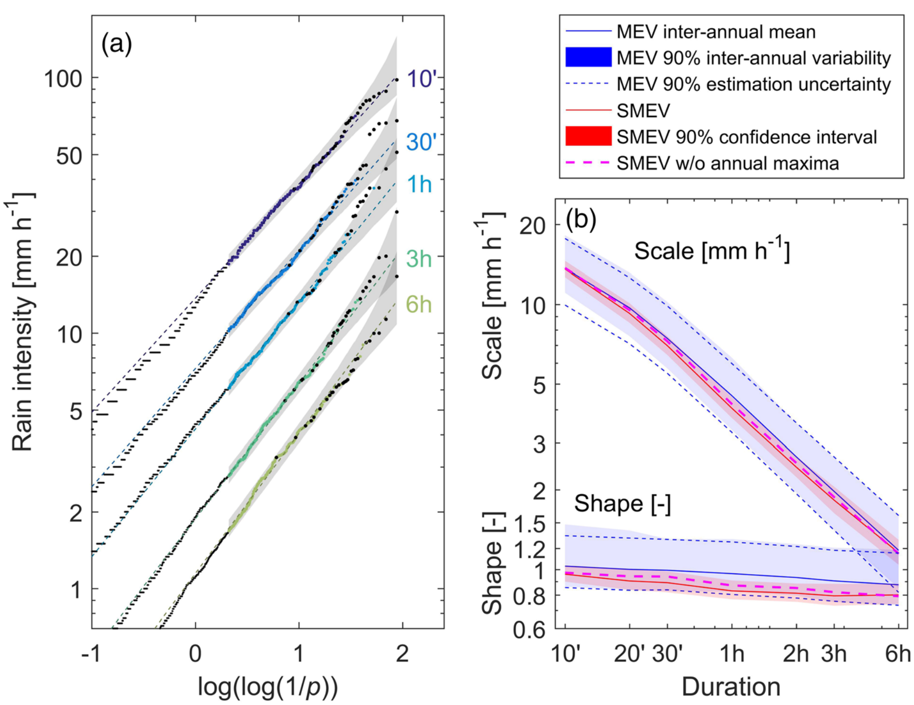

Figure 4. Robustness of MEV and SMEV assumptions. (a) Weibull plot (on the *x* axis, *p* is the exceedance probability, i.e., $1 - F$, in our notation) showing the ordinary events for the examined durations (dots, the 25% tail used in SMEV is colored according to the duration, and annual maxima are in thick black), Weibull distributions (dashed lines) whose parameters are estimated fitting the 25% tail and explicitly censoring the observed annual maxima values (thick black dots), and sampling uncertainty from the Weibull distribution (90% interval from $2 \cdot 10^3$ random samples); (b) Weibull parameters estimated using MEV and SMEV. Interannual variability of MEV parameters (blue-shaded area) almost perfectly overlaps with parameter estimation uncertainty (blue dashed lines; 10^3 random samples from a Weibull distribution described by the mean MEV parameters). SMEV parameters computed censoring the annual maxima (magenta dashed lines) are within the 90% confidence interval of the SMEV parameters (10^3 bootstrap repetitions with replacement among the years).

(dashed lines). In the examined case, which confirms what is observed in Figure 2, the whole tail of ordinary events (colored dots), including annual maxima (thick black dots), lie within the sampling confidence interval (shaded areas) and are thus likely samples from these Weibull distributions. It is worth noting that 10% of the points are expected to lie outside of this area. Additionally, the robustness of SMEV in extracting information from ordinary events emerges in that the parameters estimated censoring the annual maxima (magenta dashed lines in Figure 4b) are indistinguishable, that is, within the red-shaded confidence interval, from the ones describing the whole tail (red solid line). Despite relying on an average of more than 40 ordinary events per year, the here analyzed data did not allow to separate the interannual variability of MEV parameters (blue-shaded area in Figure 4b) from the yearly parameter estimation uncertainty (blue dashed lines).

SMEV was originally developed for climate change impact studies (Marra et al., 2019) and presents crucial advantages over other nonstationary extreme value methods. First, different event types and their different response to climate change can be independently considered. The here presented methodology can be directly extended to multiple event types using the formulation in Marra et al. (2019), thus allowing to examine climate change impacts on short-duration extremes caused by multiple types of underlying processes. Second, each event type is fully described by three parameters; this is the same number of parameters of traditional extreme value distributions, but their meaning is directly related to the physical processes as one parameter is related to the number of yearly events and two parameters to the intensity of the ordinary events. Ordinary events are better resolved in climate models than extremes, and detection and understanding of trends and changes in ordinary events is easier due to the smaller inherent stochastic uncertainty. Changes in short-duration extremes, or in any duration in general, can be thus included in the formulation by exploiting synoptic-scale information from climate models (e.g., increased/decreased occurrence of precipitating synoptic conditions), covariates explaining extreme precipitation intensities (e.g., Roderick et al., 2020), and projected changes in intrastorm structure (e.g., Peleg et al., 2018; Wasko et al., 2016).

4. Closing Statement

We proposed a consistent definition of ordinary events based on independent storms to use the MEV framework across durations and suggested the SMEV as an option to deal with extremes emerging from the tail of the ordinary events rather than their entire distribution. This definition of ordinary events allowed to effectively use MEV methods for subdaily extreme precipitation frequency analyses and permitted a scaling representation in which ordinary events scale with the same exponent of the observed annual maxima. Owing to its focus on the tail of the ordinary events distribution, SMEV provided estimates of 100 yr quantiles with less than 10% error (12.5% for the 500 yr event) with respect to a regional estimate obtained from nine stations, from only 26 yr of data (up to ~20% for MEV). These results support the use of MEV methods for subdaily and subhourly precipitation frequency analyses and are open to the use of analytical frameworks exploiting these methods across durations. This study provided a proof of concept at one location and focusing on a single type of ordinary events; further tests of the approach in other regions with different climates and precipitation mechanism could help understand the utility of the method on wider scales. Applications of the approach could improve our knowledge of extreme subdaily precipitation at the global scale with important implications for hydraulic design and risk management. Additionally, the analysis of SMEV parameters could help investigate local properties of extreme precipitation that are generally masked by the stochastic uncertainties characterizing the sampling of extremes, such as their response to local and climate forcing.

Conflict of Interest

The authors declare no conflict of interest.

Data Availability Statement

Precipitation data were provided by the Israel Meteorological Service and can be retrieved online (from http://www.ims.gov.il). Codes and data produced in the study are available online (at https://doi.org/10.5281/zenodo.3971558).

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References

Burlando, P., & Rosso, R. (1996). Scaling and multiscaling models of depth-duration-frequency curves for storm precipitation. *Journal of Hydrology*, *187*(1–2), 45–64. https://doi.org/10.1016/S0022-1694(96)03086-7

Ceresetti, D., Molinié, G., & Creutin, J.-D. (2010). Scaling properties of heavy rainfall at short duration: A regional analysis. *Water Resources Research*, *46*, W09531. https://doi.org/10.1029/2009WR008603

Davison, A. C., & Smith, R. L. (1990). Models for exceedances over high thresholds. *Journal of the Royal Statistical Society, Series B (Methodological)*, *52*(3), 393–425. https://doi.org/10.1111/j.2517-6161.1990.tb01796.x

Emmanouil, S., Langousis, A., Nikolopoulos, E. I., & Anagnostou, E. N. (2020). Quantitative assessment of annual maxima, peaks-over-threshold and multifractal parametric approaches in estimating intensity-duration-frequency curves from short rainfall records. *Journal of Hydrology*, *589*, 125151. https://doi.org/10.1016/j.jhydrol.2020.125151

Hosking, J. R. M. (1990). L-moments: Analysis and estimation of distributions using linear combinations of order statistics. *Journal of the Royal Statistical Society, Series B (Methodological)*, *52*(1), 105–124. https://doi.org/10.1111/j.2517-6161.1990.tb01775.x

Hosking, J. R. M., & Wallis, J. R. (1997). Regional frequency analysis: An approach based on L-moments. Cambridge University Press, UK. https://doi.org/10.1017/cbo9780511529443

Innocenti, S., Mailhot, A., & Frigon, A. (2017). Simple scaling of extreme precipitation in North America. *Hydrology and Earth System Science*, *21*(11), 5823–5846. https://doi.org/10.5194/hess-21-5823-2017

Langousis, A., & Veneziano, D. (2007). Intensity-duration-frequency curves from scaling representations of rainfall. *Water Resources Research*, *43*, W02422. https://doi.org/10.1029/2006WR005245

Marani, M., & Ignaccolo, M. (2015). A metastatistical approach to rainfall extremes. *Advances in Water Resources*, *79*, 121–126. https://doi.org/10.1016/j.advwatres.2015.03.001

Marra, F., Nikolopoulos, E. I., Anagnostou, E. N., & Morin, E. (2018). Metastatistical extreme value analysis of hourly rainfall from short records: Estimation of high quantiles and impact of measurement errors. *Advances in Water Resources*, *117*, 27–39. https://doi.org/10.1016/j.advwatres.2018.05.001

Marra, F., Zoccatelli, D., Armon, M., & Morin, E. (2019). A simplified MEV formulation to model extremes emerging from multiple nonstationary underlying processes. *Advances in Water Resources*, *127*, 280–290. https://doi.org/10.1016/j.advwatres.2019.04.002

Miniussi, A., & Marani, M. (2020). Estimation of daily rainfall extremes through the metastatistical extreme value distribution: Uncertainty minimization and implications for trend detection. *Water Resources Research*, *56*, e2019WR026535. https://doi.org/10.1029/2019WR026535

Miniussi, A., Villarini, G., & Marani, M. (2020). Analyses through the metastatistical extreme value distribution identify contributions of tropical cyclones to rainfall extremes in the eastern United States. *Geophysical Research Letters*, *47*, e2020GL087238. https://doi.org/10.1029/2020GL087238

Nadarajah, S., Cordeiro, G. M., & Ortega, E. M. M. (2013). The exponentiated Weibull distribution: A survey. *Statistical Papers*, *54*(3), 839–877. https://doi.org/10.1007/s00362-012-0466-x

Overeem, A., Buishand, A., & Holleman, I. (2008). Rainfall depth-duration-frequency curves and their uncertainties. *Journal of Hydrology*, *348*(1–2), 124–134. https://doi.org/10.1016/j.jhydrol.2007.09.044

Papalexiou, S. M. (2018). Unified theory for stochastic modelling of hydroclimatic processes: Preserving marginal distributions, correlation structures, and intermittency. *Advances in Water Resources*, *115*, 234–252. https://doi.org/10.1016/j.advwatres.2018.02.013

Papalexiou, S. M., AghaKouchak, A., & Foufoula-Georgiou, E. (2018). A diagnostic framework for understanding climatology of tails of hourly precipitation extremes in the United States. *Water Resources Research*, *54*, 6725–6738. https://doi.org/10.1029/2018WR022732

Peleg, N., Marra, F., Fatichi, S., Molnar, P., Morin, E., Sharma, A., & Burlando, P. (2018). Intensification of convective rain cells at warmer temperatures observed from high-resolution weather radar data. *Journal of Hydrometeorology*, *19*(4), 715–726. https://doi.org/10.1175/JHM-D-17-0158.1

Restrepo-Posada, P. J., & Eagleson, P. S. (1982). Identification of independent rainstorms. *Journal of Hydrology*, *55*(1–4), 303–319. https://doi.org/10.1016/0022-1694(82)90136-6

Roderick, T. P., Wasko, C., & Sharma, A. (2020). An improved covariate for projecting future rainfall extremes? *Water Resources Research*, *56*, e2019WR026924. https://doi.org/10.1029/2019WR026924

Schellander, H., Lieb, A., & Hell, T. (2019). Error structure of metastatistical and generalized extreme value distributions for modeling extreme rainfall in Austria. *Earth and Space Science*, *6*, 1616–1632. https://doi.org/10.1029/2019EA000557

Serinaldi, F., Lombardo, F., & Kilsby, C. G. (2020). All in order: Distribution of serially correlated order statistics with applications to hydrological extremes. *Advances in Water Resources*, *144*, 103686. https://doi.org/10.1016/j.advwatres.2020.103686

Tarolli, P., Borga, M., Morin, E., & Delrieu, G. (2012). Analysis of flash flood regimes in the north-western and south-eastern Mediterranean regions. *Natural Hazards and Earth System Sciences*, *12*(5), 1255–1265. https://doi.org/10.5194/nhess-12-1255-2012

Wasko, C., Sharma, A., & Westra, S. (2016). Reduced spatial extent of extreme storms at higher temperatures. *Geophysical Research Letters*, *43*, 4026–4032. https://doi.org/10.1002/2016GL068509

Zorzetto, E., Botter, G., & Marani, M. (2016). On the emergence of rainfall extremes from ordinary events. *Geophysical Research Letters*, *43*, 8076–8082. https://doi.org/10.1002/2016GL069445

Zorzetto, E., & Marani, M. (2020). Extreme value metastatistical analysis of remotely sensed rainfall in ungauged areas: Spatial downscaling and error modeling. *Advances in Water Resources*, *135*, 103483. https://doi.org/10.1016/j.advwatres.2019.103483